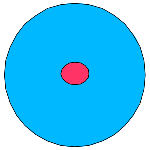
The Thermonuclear Runaway in SNe Ia
(How to run away?)

by P. Hoeflich (Austin) & J. Stein (Jerusalem)

- Introduction and open questions
- 2-D calculations for the thermonuclear runaway
- Discussions and conclusions

Scenarios: What do we observe as a SNe Ia?

Thermonuclear explosion of a white dwarf



1) Hydrodynamical phase

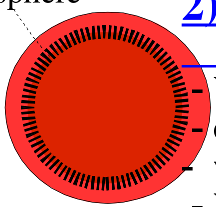
- sudden release of about 2E51 erg by nuclear burning of a WD

=> object becomes unbound

Duration of hydrodynamical phase: several sound crossing times

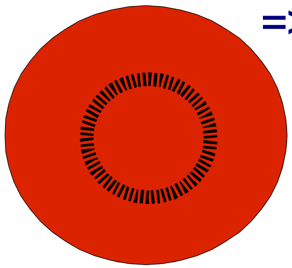
- sound velocity is about 5,000 to 10,000km/sec
- radius of objects 1500km(WD)

=> hydrodynamical time scale lasts seconds



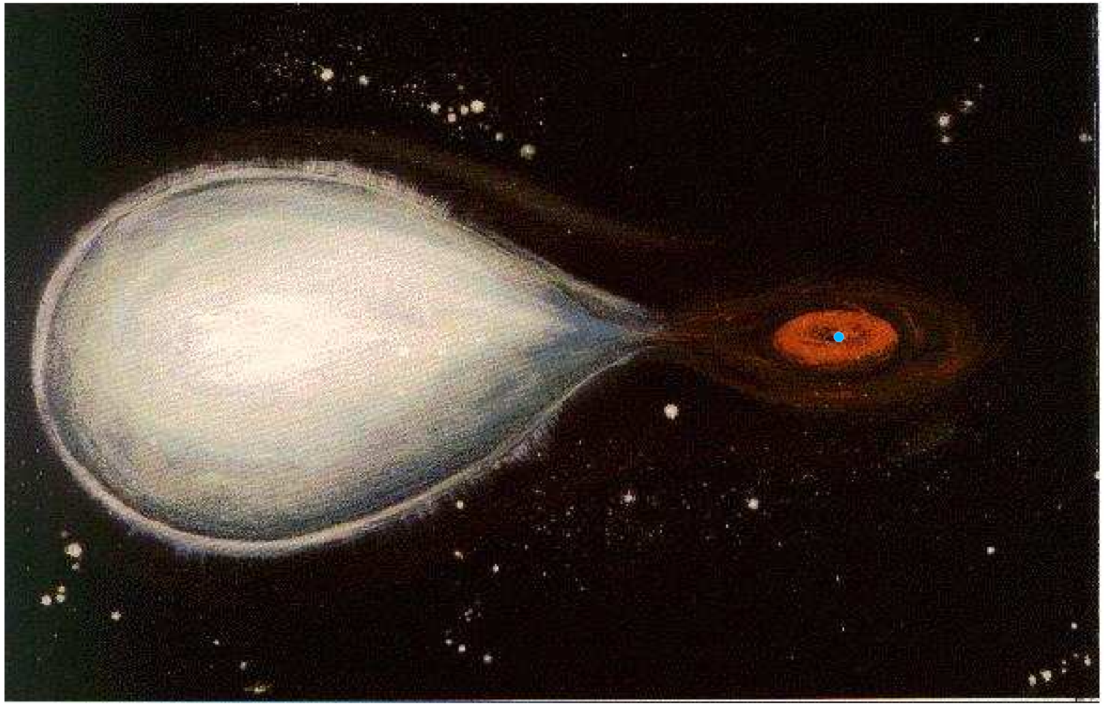
2) Subsequently: Phase of free expansion (homologeous phase)

- We observe a rapidly expanding envelope as a the results of the explosion !!!
- expansion velocities are 1000 to 20,000 km/sec
- we observe the light emitted from the photosphere
- With increasing time, the envelope becomes more an more transparent (due to geometrical dilution)



=> The time evolution of the emitted light allows to trace the radial density and chemical structure of the envelope !!!

1) Progenitors: Accreting White Dwarfs

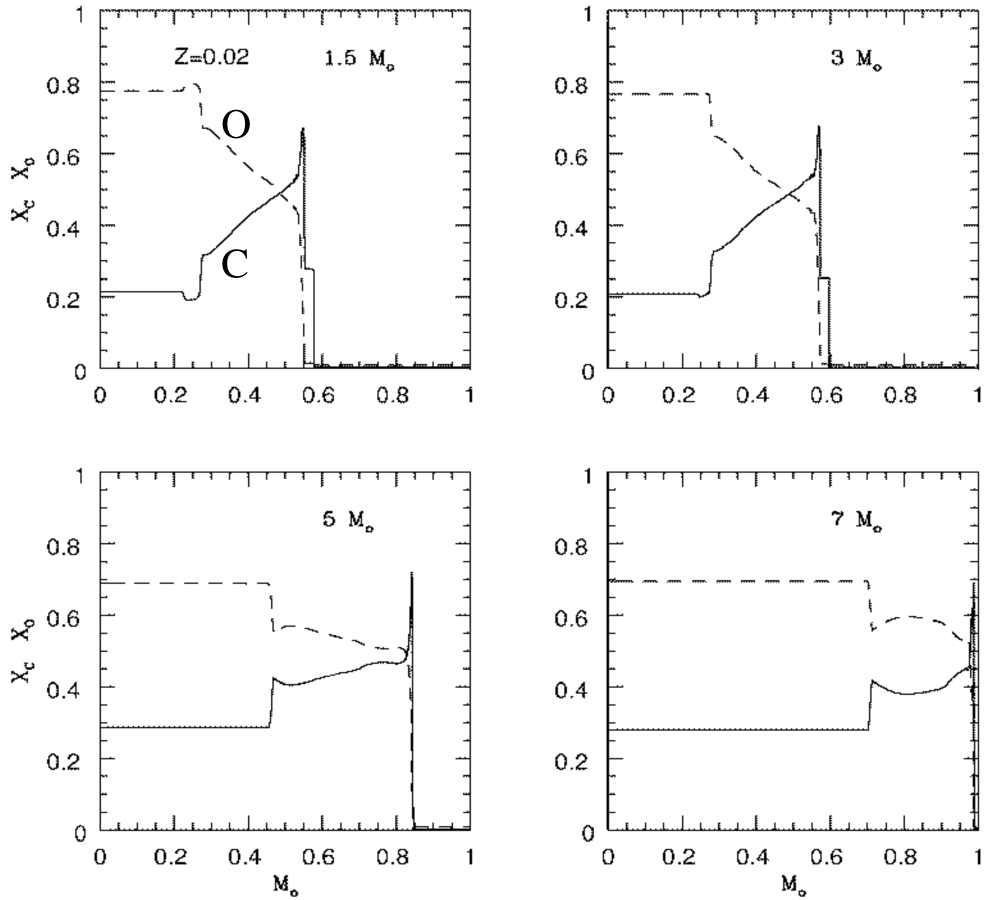


Start: WD of 0.6 to 1.2 Mo
Evolution: Accretion of H, He or C/O rich material
Explosion: Ignition when nuclear time scales are shorter than hydrodyn. TS

2) Progenitors: Merging White Dwarfs

Influence of the MS on the structure of the WD

(Dominguez, Hoeflich, Straniero 2001, ApJ 557, 279)



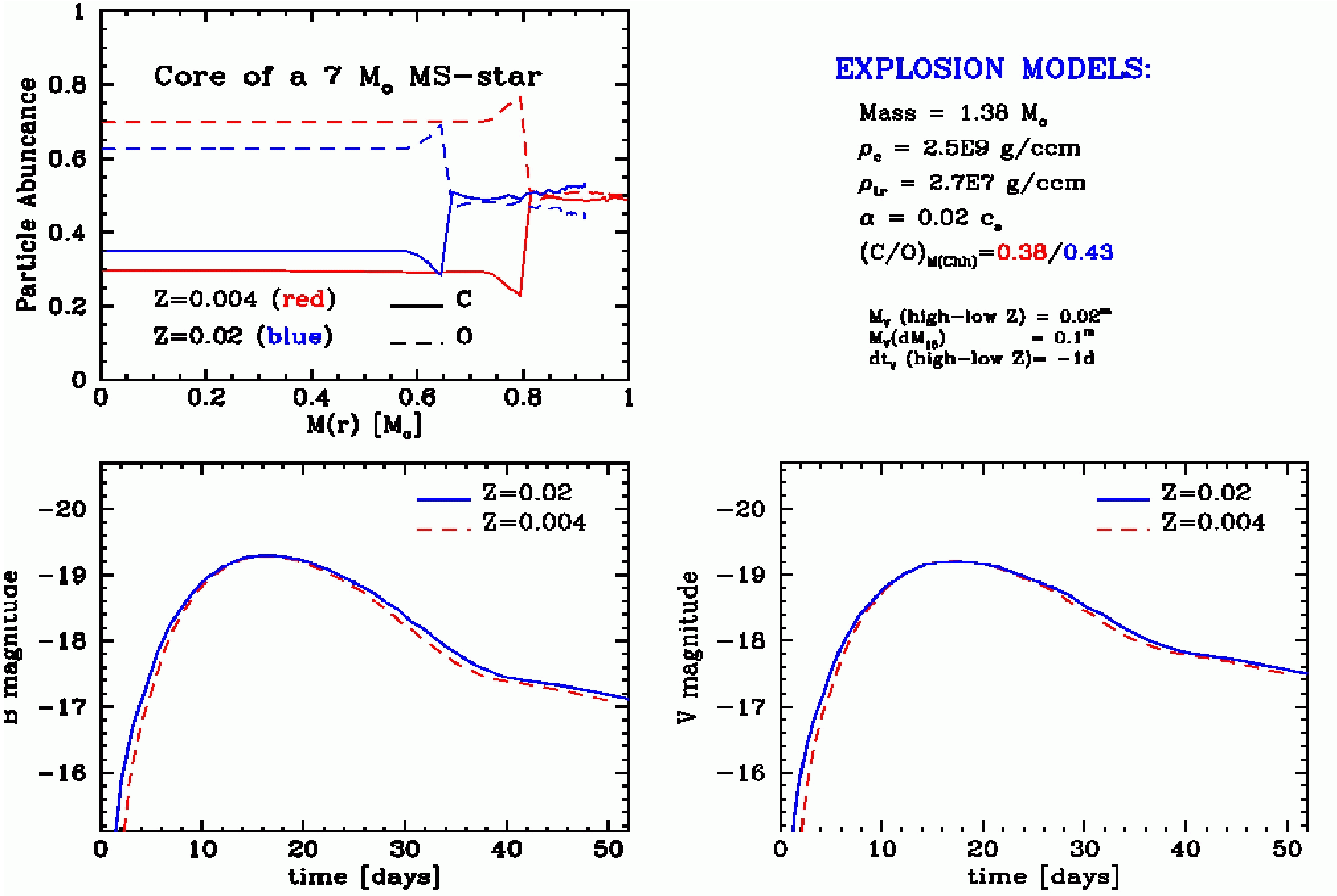
- Size of C-depleted core depends on central He burning during the stellar evolution

=> f(MS)

=> Explosion energy f(MS)

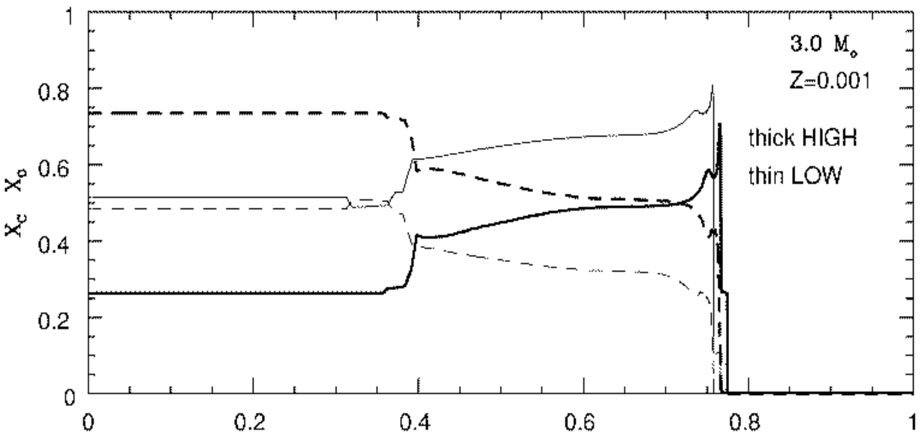
Progenitor Structures, Metallicity Dependence and Consequences for the Light Curves of SNeIa

(Hoeflich, Nomoto, Umeda & Wheeler 2000, ApJ 528, 854)



Influence of C12(alpha,gamma)O16 on the Structure

Dominguez, Hoeflich, Straniero 2001, ApJ 557, 279)

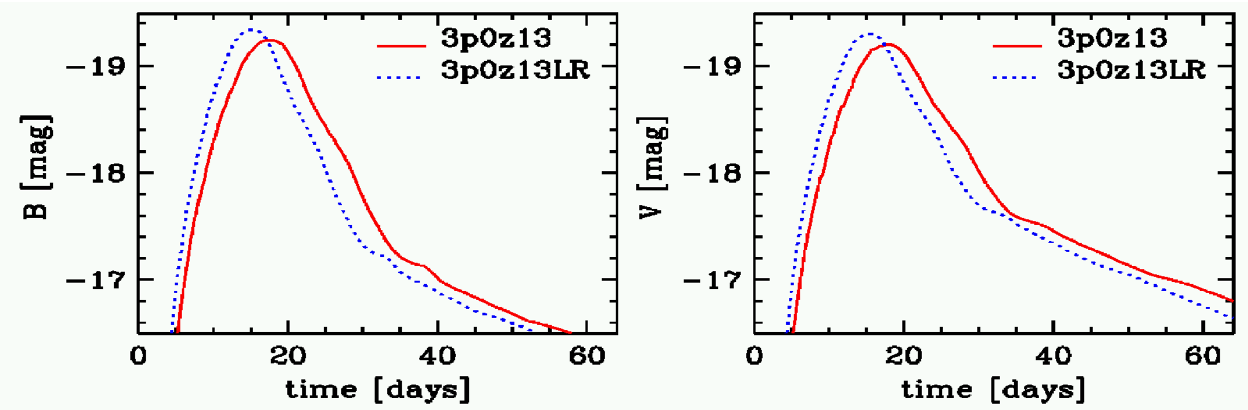


- Size of C-depleted core depends on the nuclear reaction rate (uncertainty fac. 5)

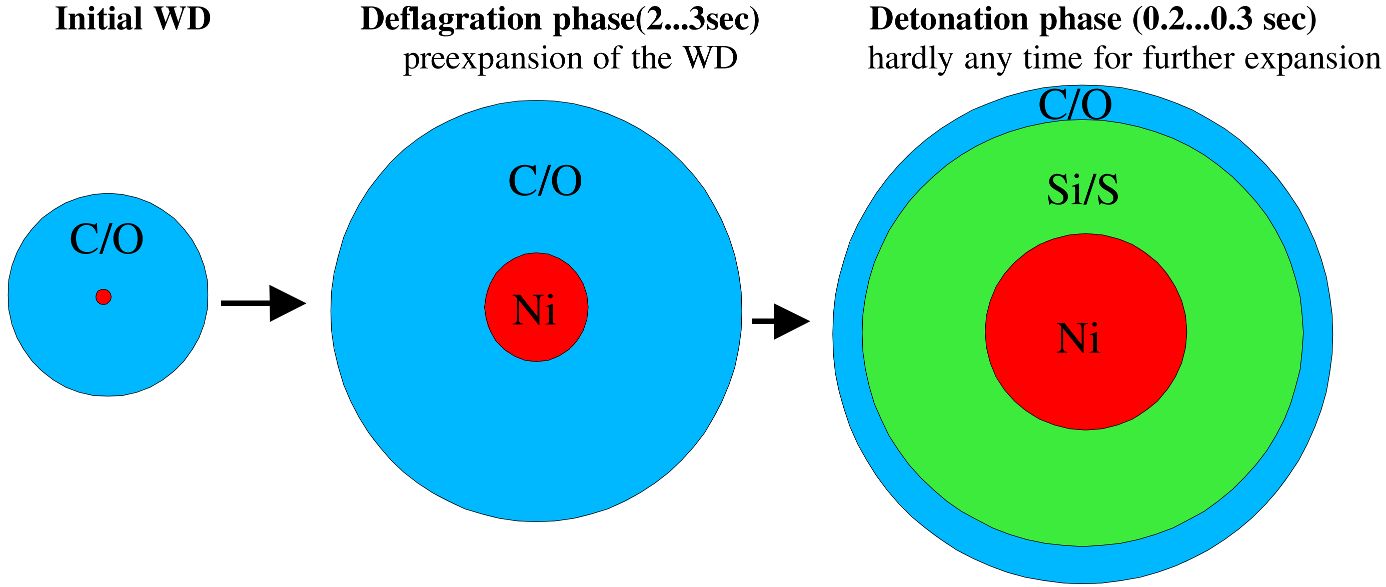
Caughlan et al. 1985, At.Data Nuc. Tab. 32, 197

Caughlan & Fowler 1988, At.Data Nucl. Tab 40, 283

Astrophysical Applications favor a high rate (e.g. Stellar evolution, LCs



Explosion Scenarios of White Dwarfs (Delayed Detonation)

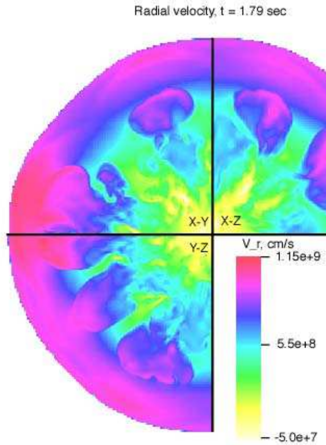


Deflagration: Energy transport by heat conduction over the front, v <<v(sound)
=> ignition of unburned fuel (C/O)

Detonation: ignition of unburned fuel by compression, v = v(sound)

Propagation of the Deflagration Front (from Khokhlov,2001, ApJ, in press)

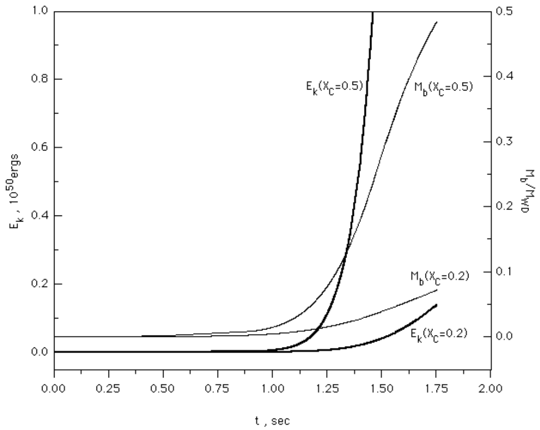
Burning of a WD at 2.5 sec (from ATP-2001 HK)



- Blobs mix into layers corresponding to about 8000 km/sec in the hom. ph.

Some Remarks:

- pre-expansion depends on the amount of burning (-> does not depend on details of burning)
- expansion becomes spherical
- but inhomogenities in the abundances
- size and amount of burning depends on C/O



Transition from Deflagration to Detonation

Possible mechanism:

1) Zeldovich mechanism: Mixing from burned and unburned material

- Problem: works only for low fluctuations in the background

2) Crossing shock waves (e.g. Livne 1997)

- Problem: Is the 'noise' sufficient or do we need some reflection at boundaries?

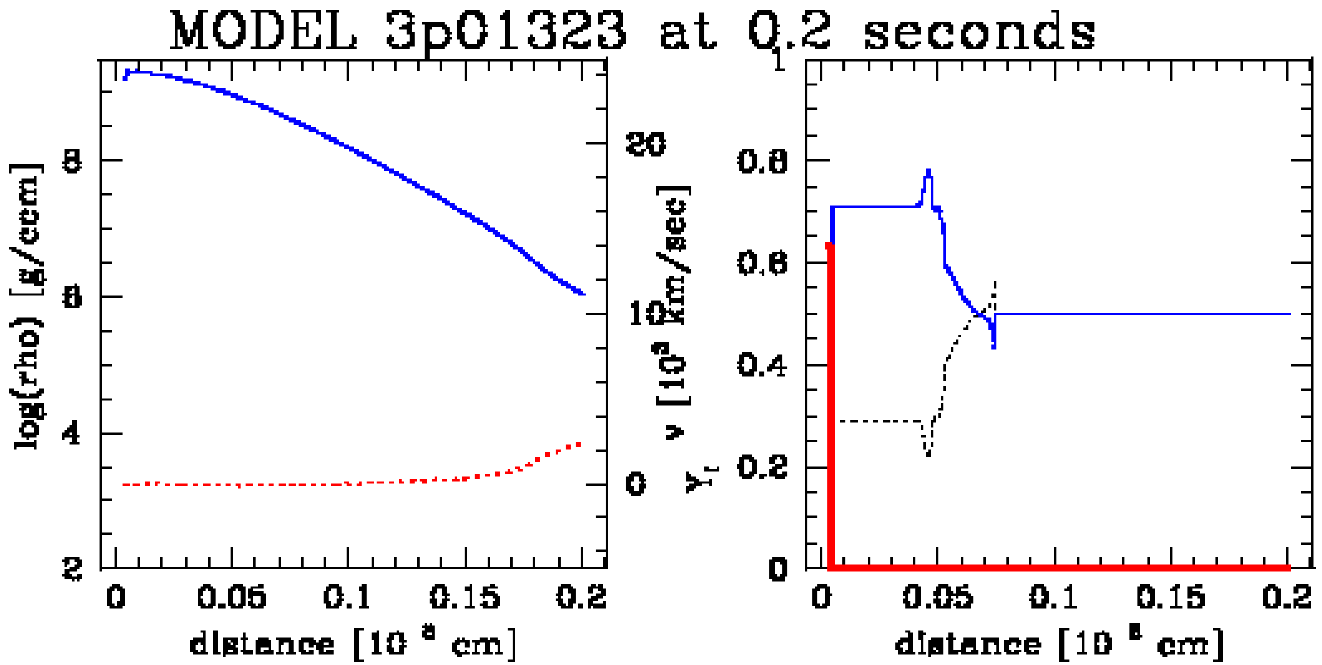
3) Shear flows at low densities (e.g. Livne/Aspen workshop)

- Problem: Does it work?

Explosion of a delayed detonation model

- progenitor : 3Mo on MS with 1/30 of solar metallicity
- Properties of WD: a) Chandrasekhar mass b) central density 2E9 g/ccm

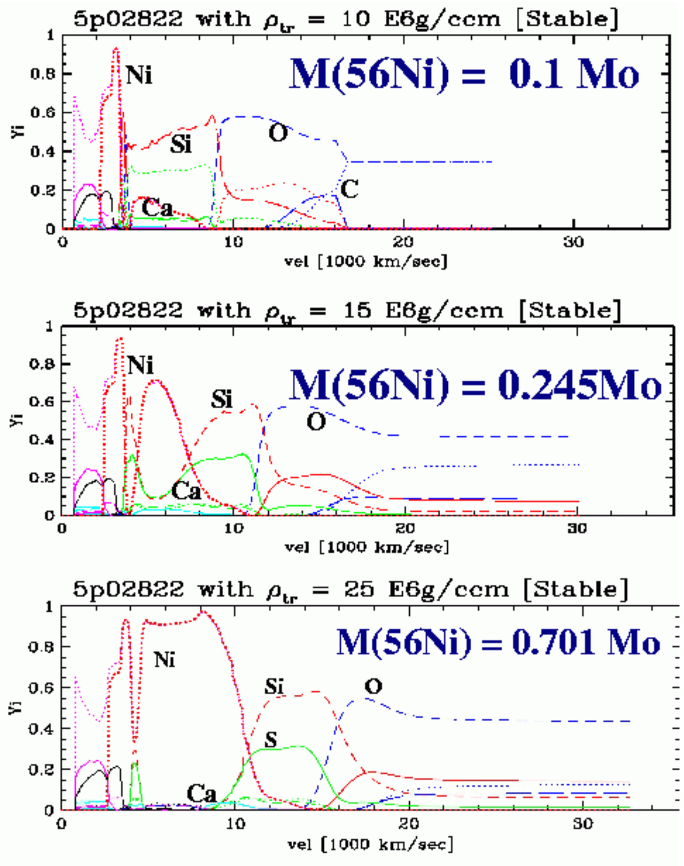
- Properties of deflagration front: a) v(defl.) with C1=0.15 b) rho(tr) = 2E7 g/ccm



red: complete b. (Fe, Co, Ni) ; **green:** incomplete b. (Si, S, ...) ; **blue:** C and O

Chemical Structures for Delayed-Detonation Models

C/O-WD; rho(c)=2.E9 g/ccm; M(MS)=5Mo



- start with slow deflagration front
  RT unstable -> acceleration

- Prompt transition to detonation

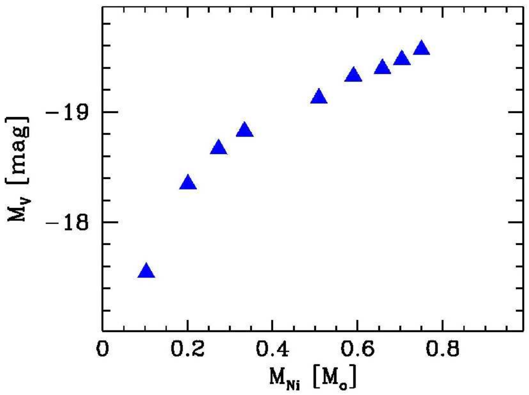
- Produces both normal bright
  and subluminous SN

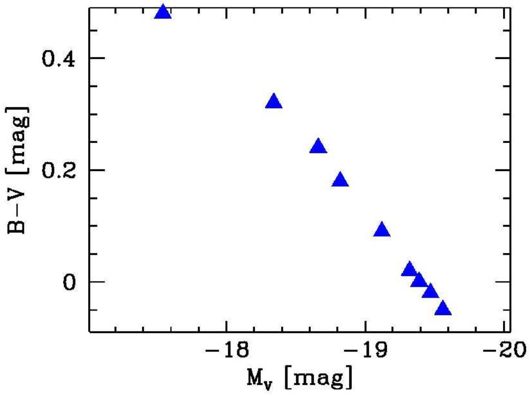
- Avoids problem electron capture at the center.
  (with new rates + adaptive mesh-hydro.
  => rho(c) may be up to 3.5E9g/ccm)

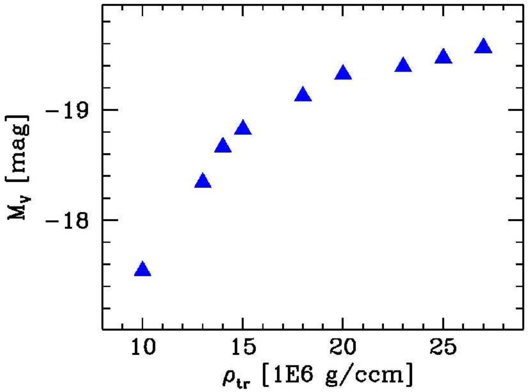
(Fits well for a lot of S NeIa)

Correlations for DD-Models

Example: rho(c)=2.E9g/ccm; M(MS)=5Mo





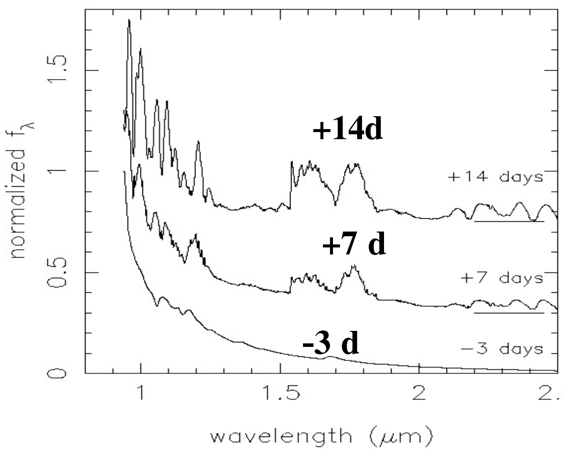


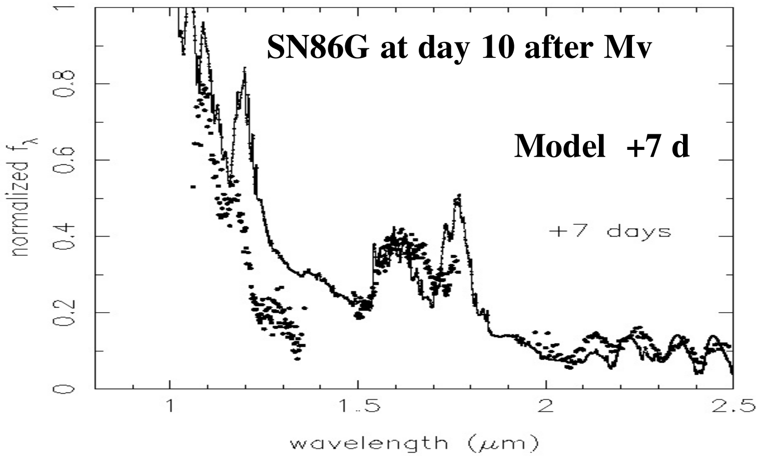
- rho(tr) determines M(Ni)
(See Hoeflich 1995)

- models are similar bright for a wide range of parameters !

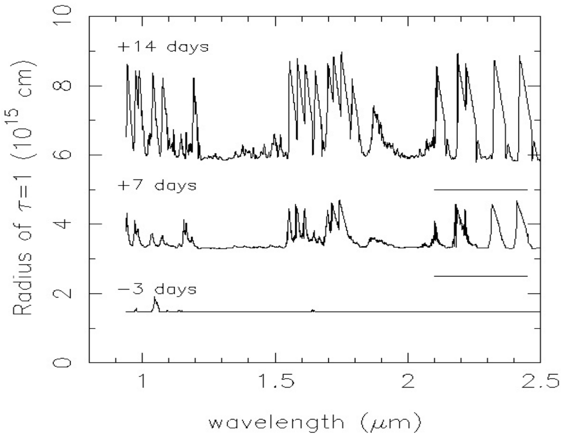
Post-maximum IR-Spectra of DD200 in Comparison with SN86G

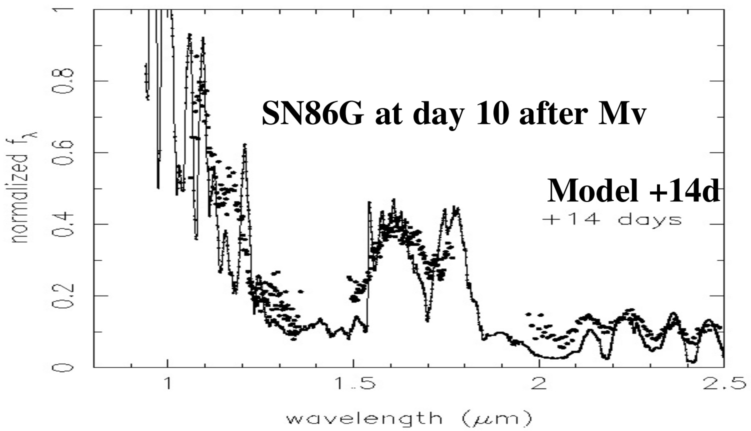
Flux between 1 and 2.5 μm





Radius between 1 and 2.5 μm

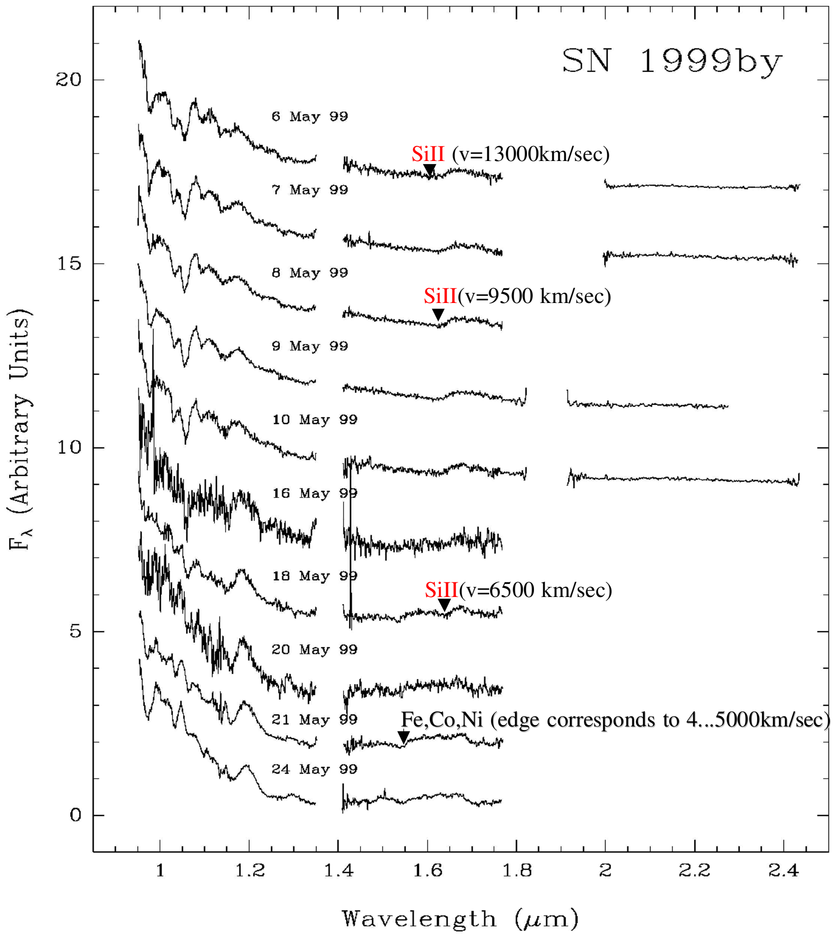




Observation of SN1986g by P. Meikle et al.

IR-Spectra of the Subluminous SN1999by

Observation by C. Gerardy (PhD thesis)

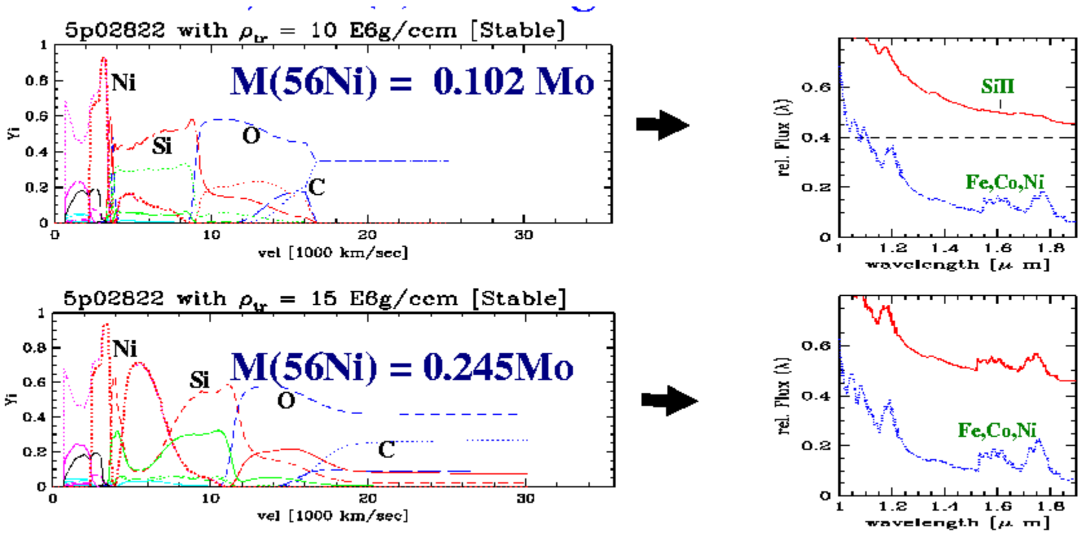


- M(V) on May 8

Rem: Quoted velocities are based
on the Doppler shift of absorption
minima
(Uncertainty is about 2000 km/sec)

Structures and IR Spectra for Subluminous DD-Models

C/O-WD; rho(c)=2.E9 g/ccm IR-flux 1 & 2 weeks after M(V)

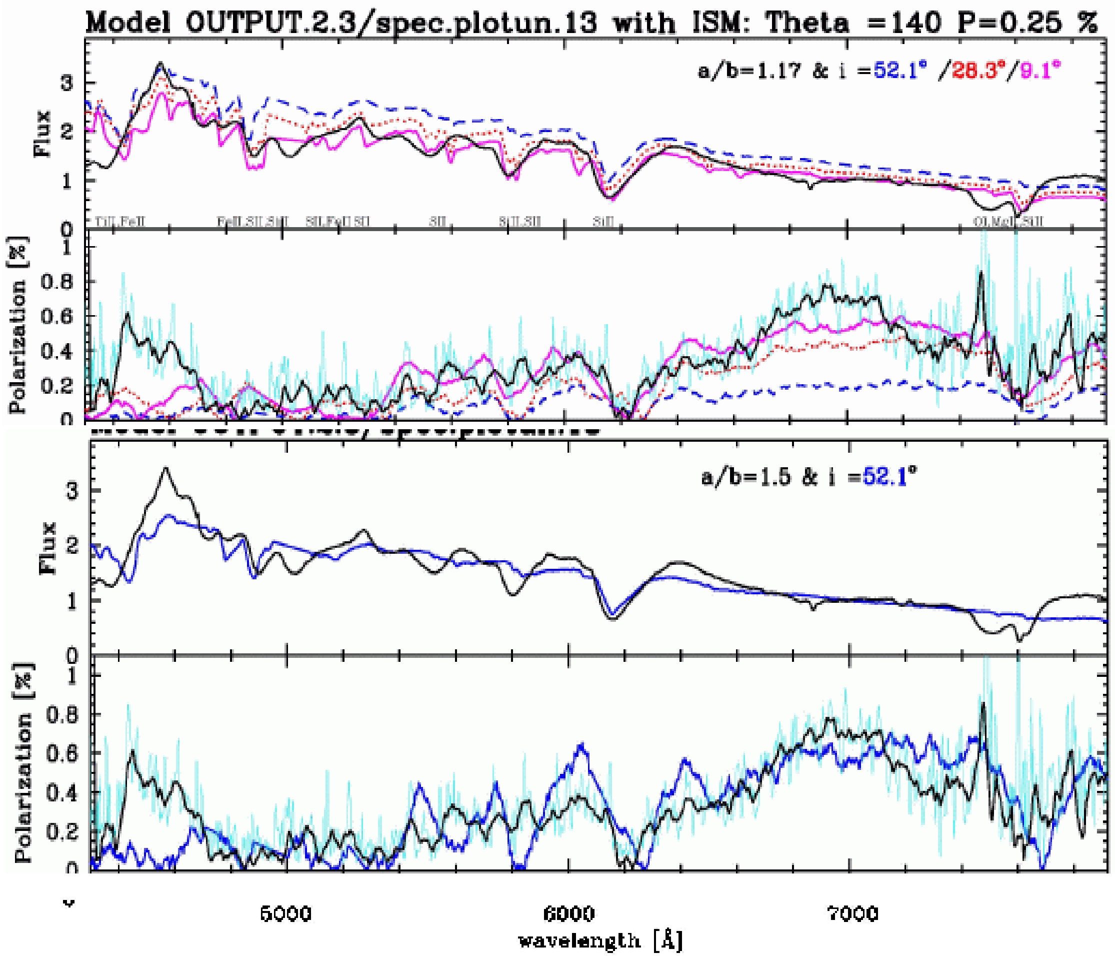


- Only very subluminous models are consistent with SN1999bu
- Layers up to 12-15000 km/sec must undergo explosive O-burning
- Strong mixing or extended Ni-tails are not allowed (PDD5 and PDD1c problems)
- Models shall not mix large blobs into the outer layers during deflagration!!!

Is this specific/the reason for subluminous SNeIa ???

Polarization of the subluminous SN1999bu vs. prolate model

(PhD thesis of A. Howell & Howell, Hoeflich, Wang, Wheeler, ApJ, in press)



- global asymmetry
- asphericity 17 %
- seen equator on

- larger axis + higher inclination does not work

Possible explanation rapidly rotating WD

=> The explosion is determined by the preconditioning of the WD

- the propagation of the deflagration front depends on the C/O ratio

- the DD-transition may depend on
  a) the C/O ratio
  b) the location and jump in the chemical profiles of the WD

- Subluminous SNIa may be produced by rapid rotation of a WD

Questions

- Does the chemical profile 'survives' on the way to the runaway?

- Does the thermonuclear runaway occur in multiple spots?

- Does we start off with a static WD?

Models for the Progenitor Evolution

A) Spherical accretion models

Physics:

- implicit, quasi-static evolution in first order for the standard stellar structure equation (Hoeflich et al. 1998)
- energy transport by
  - a) conduction (Itoh et al. 1983)
  - b) convection in the mixing length theory
  - c) radiative diffusion including Kramer's and ff-opacities
- detailed nuclear network (35 nuclei up to 24Mg)
- detailed equation of state (Nomoto et al. 1982)
- thermal pulsed of H/He burning are treated by Sato (1980)

Recipe:

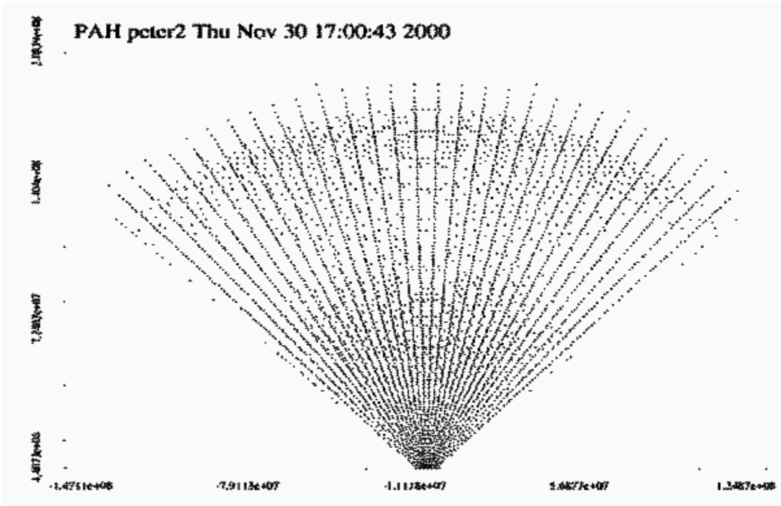
- Take the core of a star (M<8Mo) at the end of He burning
- Accrete H, He or C/O material with a given rate
- Follow the evolution over 1E6 to 1E8 years up to the explosion

B) Follow the last few hours till runaway in multi-D

Physics:
- implicit, 2-D hydrodynamic equations in first order in time
- interpolated energy for nuclear burning calibrated by detailed network
- detailed equation of state

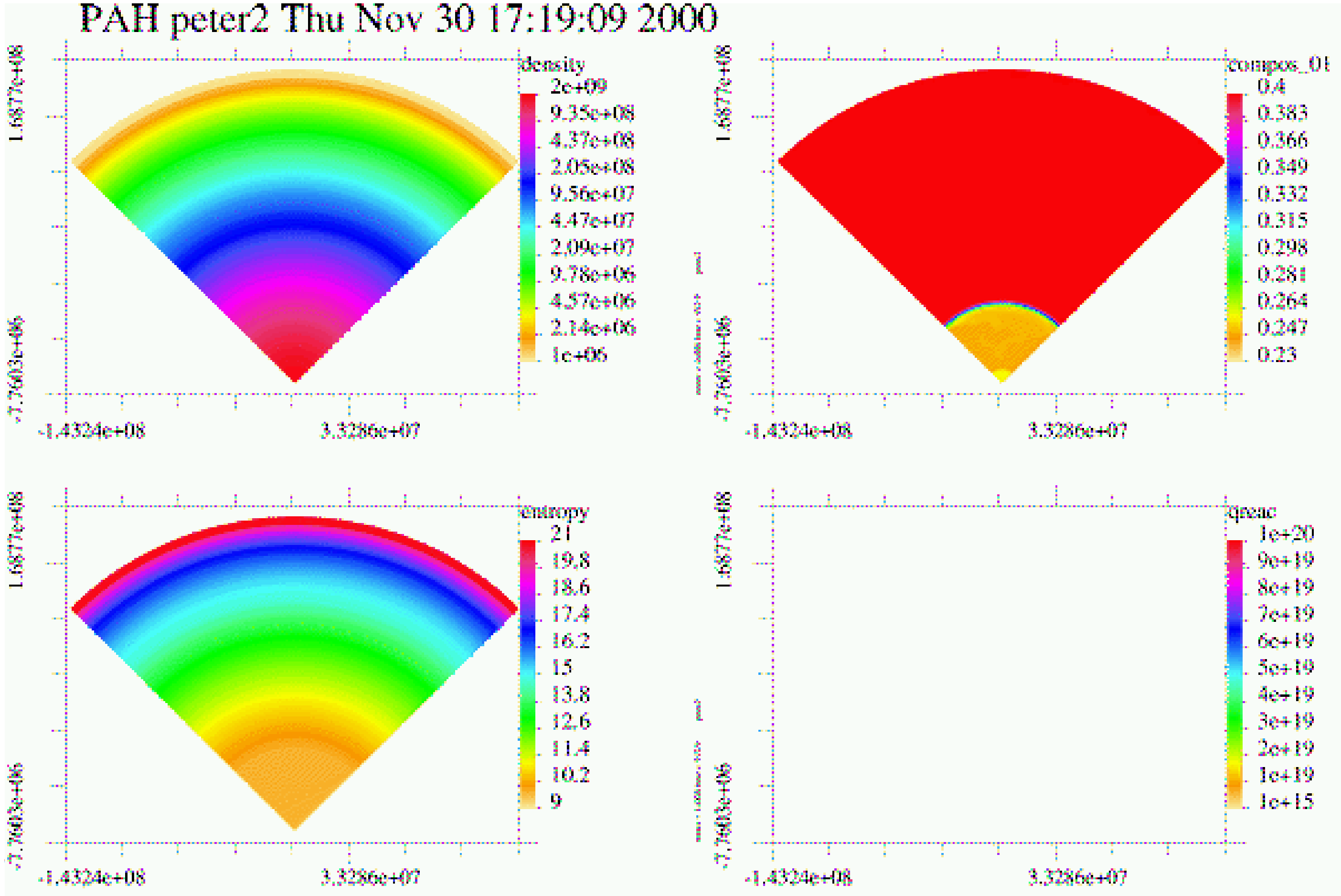
Recipe:
- Remap 1-D structure at about 5 hours before runaway and follow the evolution

Domain: 2.08E8cm
Logarithm grid in r
Grid(r/theta): (191/31)



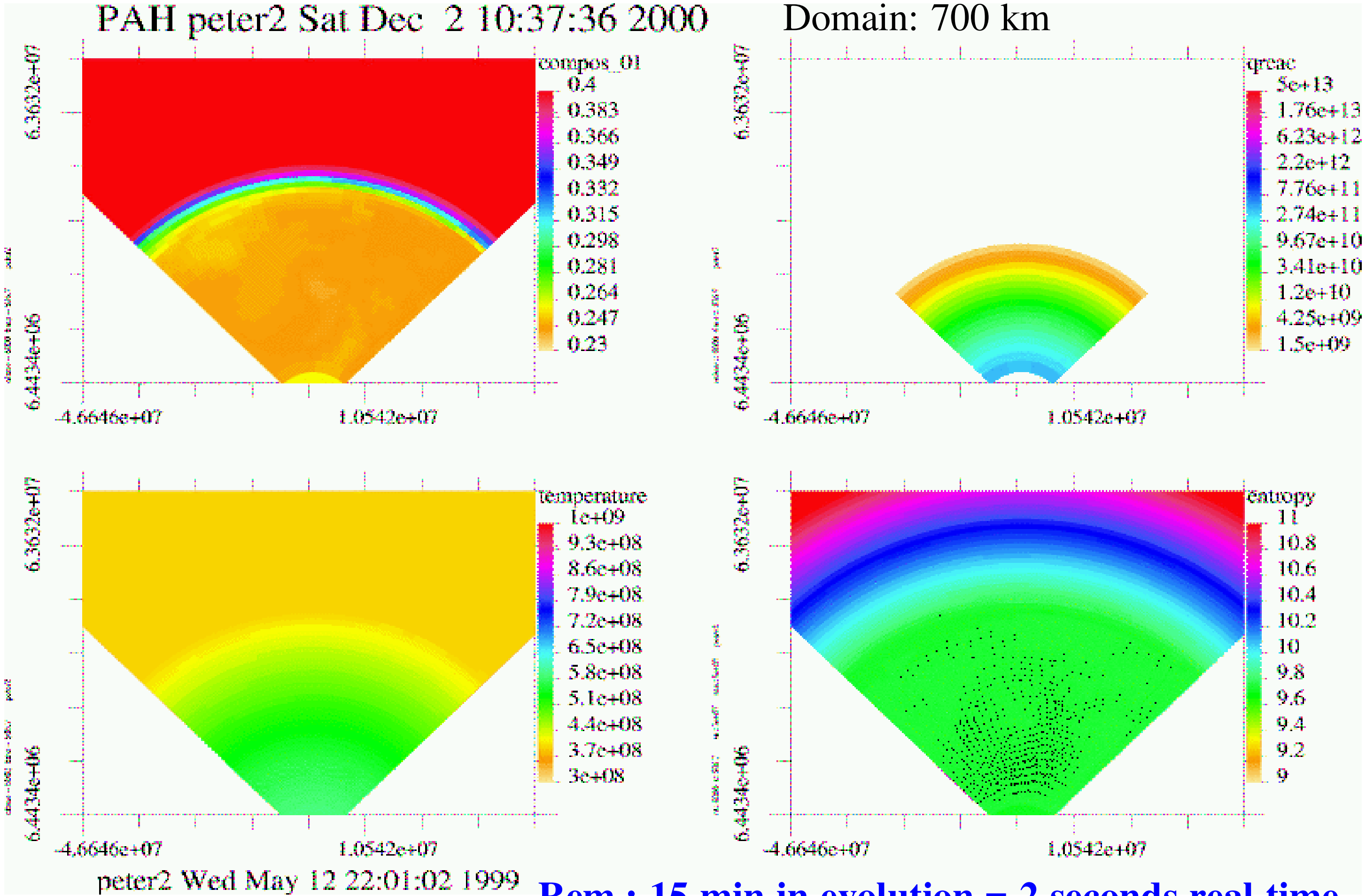
The thermonuclear runaway of a WD (Hoeflich&Stein,2002,ApJ, in press)

Initial structure 2 hours before runaway



The thermonuclear runaway of a WD

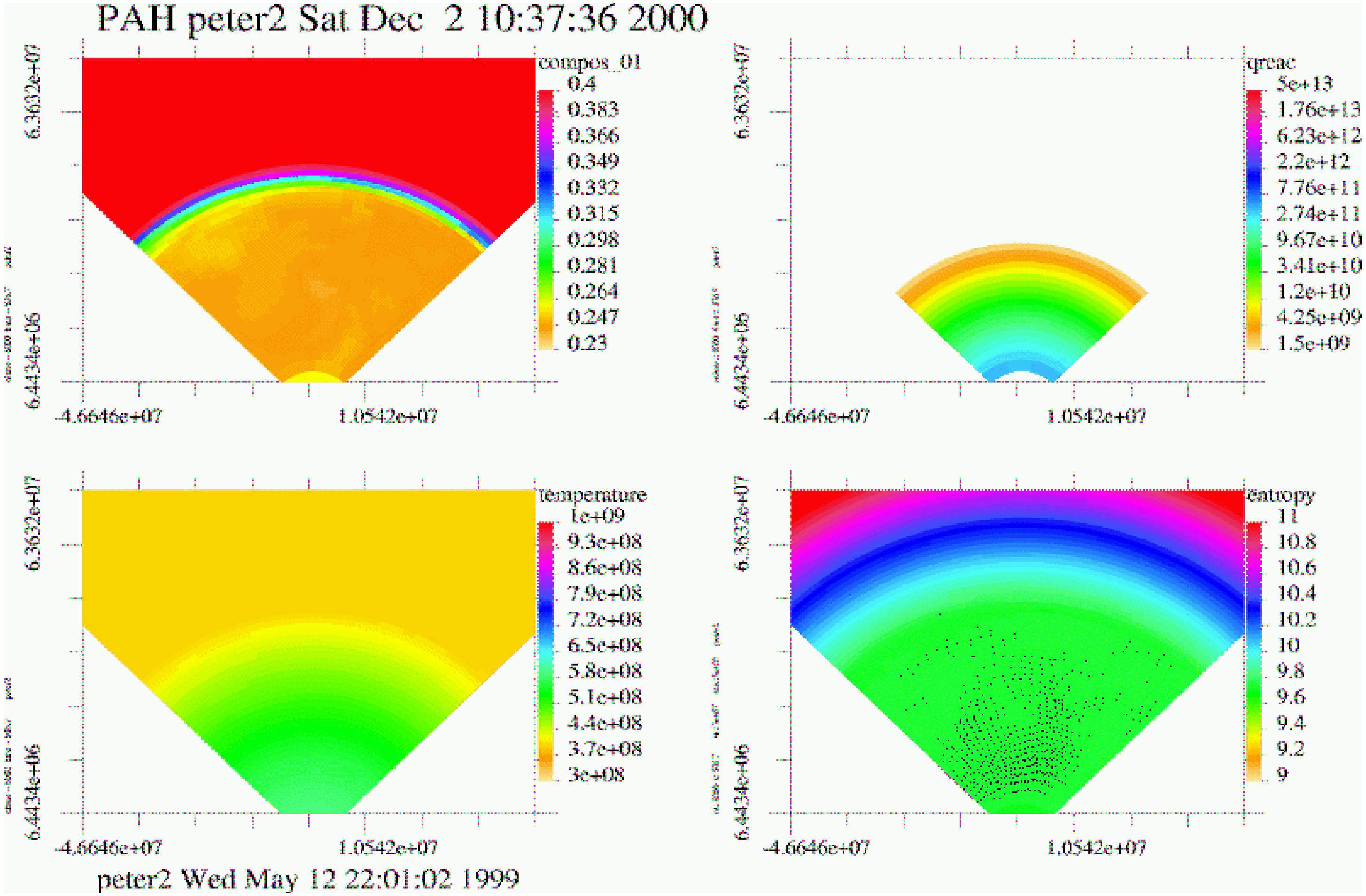
Time evolution from -3 to -0.5 hours with Dt=0.5h and at -900, -450, -225, -1 sec



Rem.: 15 min in evolution = 2 seconds real time

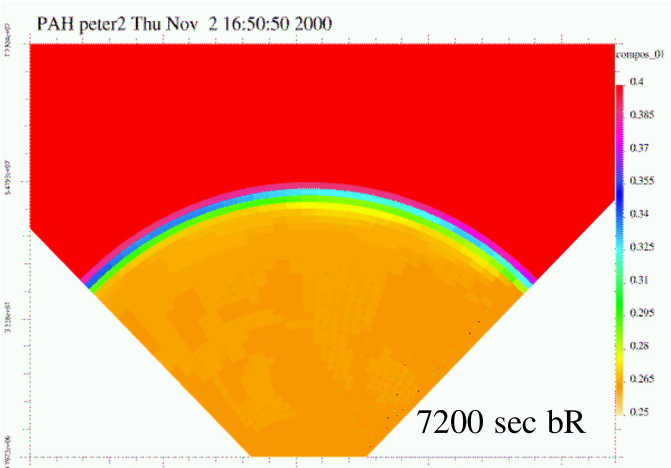
The thermonuclear runaway of a WD

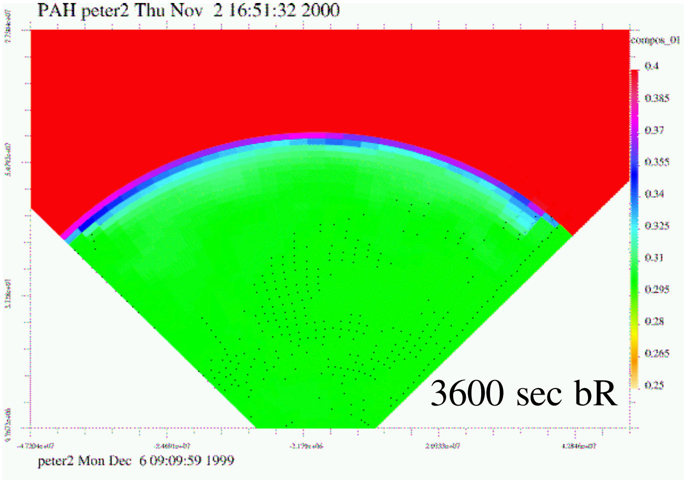
Time evolution from -3 to -0.5 hours with Dt=0.5h and at -900, -450, -225, -1 sec

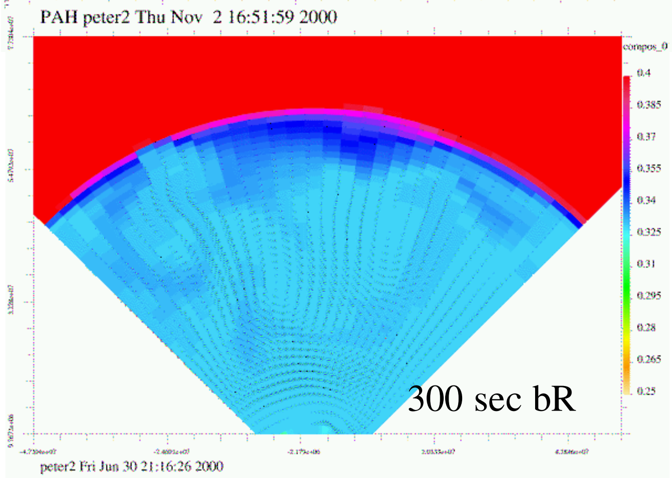


The thermonuclear runaway of a WD

a) Change of C/O and velocity in the WD (Mch, M(MS)=3Mo)



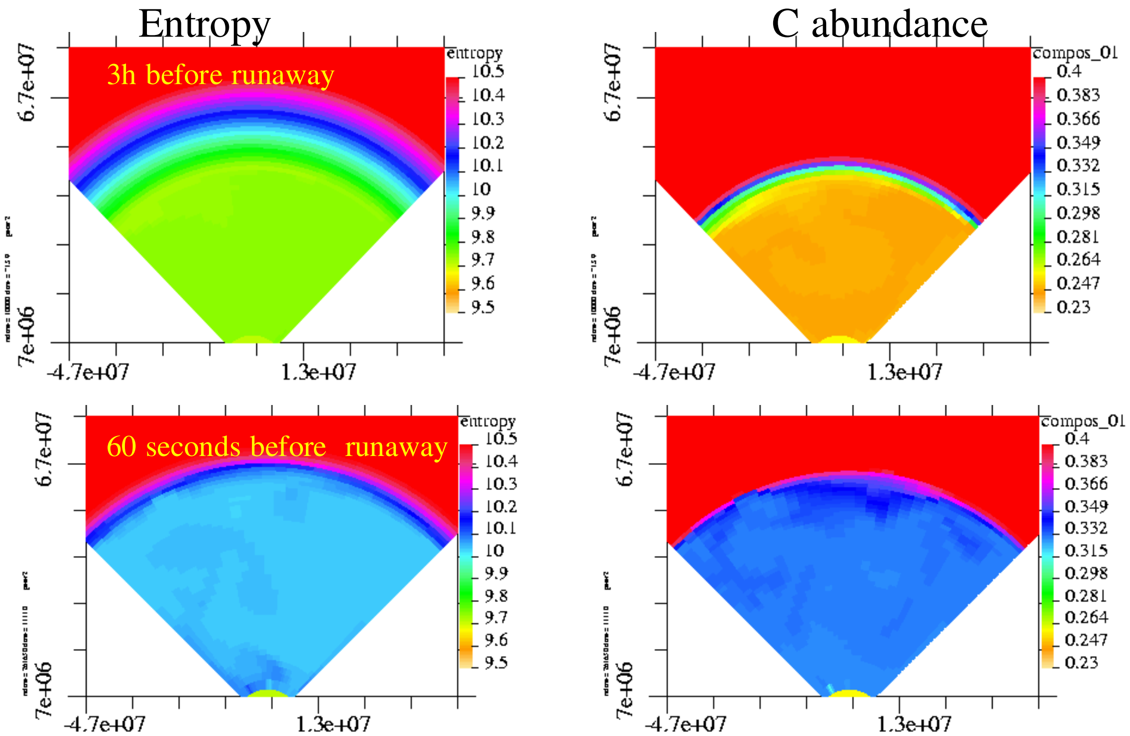




Change of the CO before runaway

velocities (longest = 100 km/sec)

How to estimate the final C abundance in the center ?



- entropy is almost constant in the convective center

- runaway occurs at an mean entropy is about 10.1 (up from about 9.7)

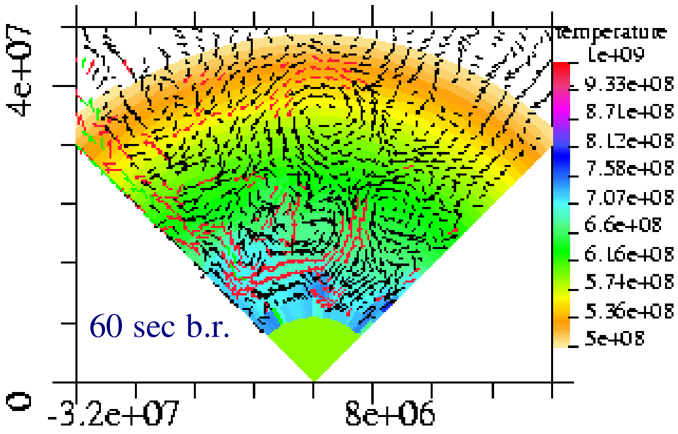
- C originates from to mixing in of C-rich material (not the nuclear burning)

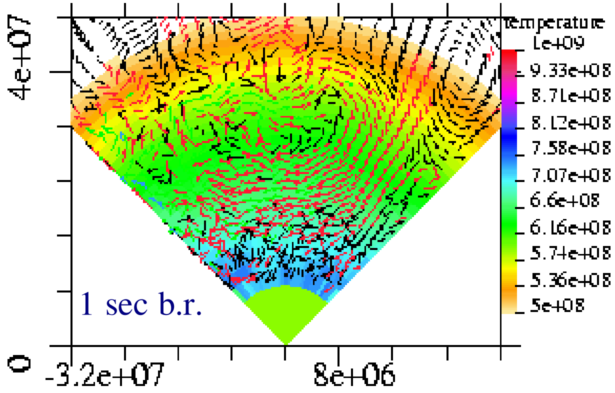
=> Determine the radius of entropy corresponding to the runaway and mix to estimate C

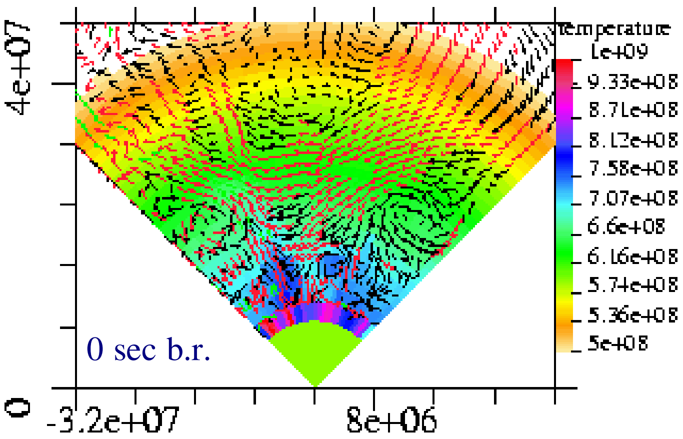
Corrolar: 'Classical' overshooting is not allowed

Temperature and velocity evolution before runaway

Longest velocity vector (black,red,green) =(40/80/120 km/sec) ; 500E8 K< T < 1.E9 K





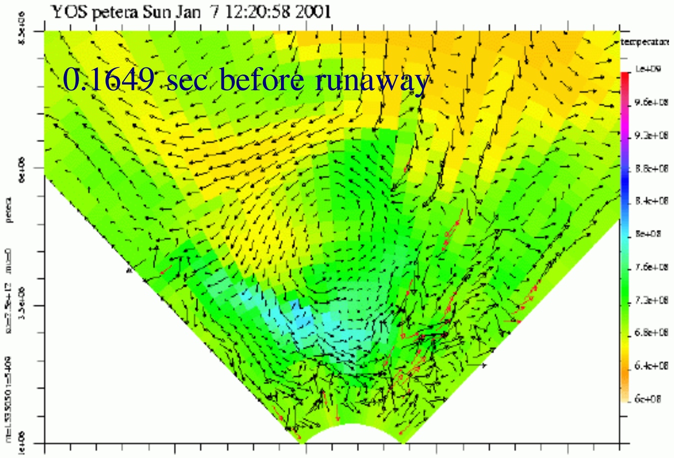


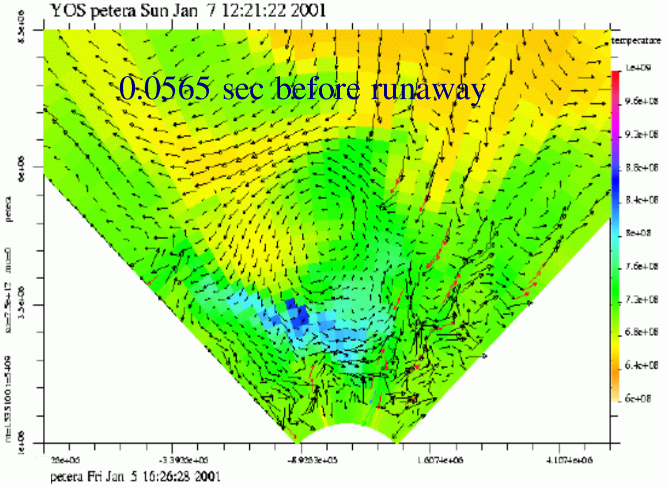
- size of shown domain: 420 km
- size of WD 1800 km
- ignition close to the center at within one cell (about 5km resolution, <65km)
- ignition occus due to compression of an element due to circulation when the mean T8 of the turbulent element > 9

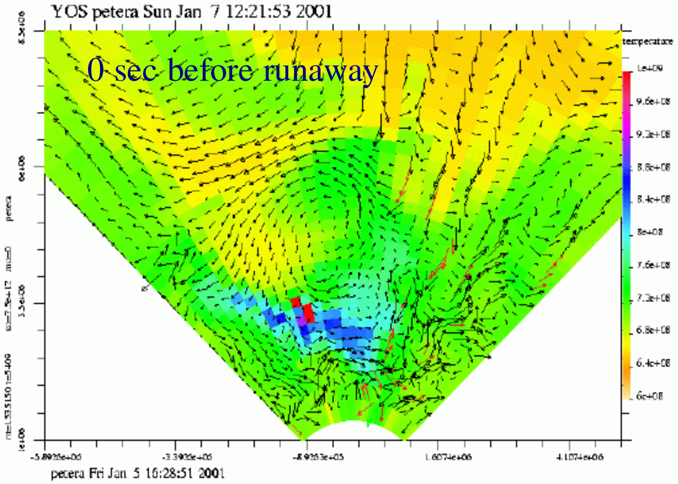
- v(turb) > v(lam) => early phase of nuclear burning is governed by preconditioning of WD

Temperature and velocity evolution before runaway

Longest velocity vector in black = 50 km/sec ; 600E8 K< T < 1E9 K







- size of shown domain: 100 km
- size of inner boundary: 13.7 km
- ignition close to the center at within one cell (about 27 km)
- ignition occus due to compression of an element due to circulation when the mean T8 of the turbulent element > 9

- v(turb) > v(lam) => early phase of nuclear burning is governed by preconditioning of WD

Some Uncertainties and Open Questions

a) C12(alpha,gamma)O16 reaction rate

Influence on the ignition point:

Enhancement factor F	Change of final C-concentration	Distance of ignition
200	26 +- 1 %	90 km
50	32.5	86 km
20	35.5	71 km
4	36.2	32 km
1	37.0	27 km

=> likely, no qualitative change of the results

b) Some limitations (just mentioned)

- problem of invers cascades (for incompressible fluids)

(statistically, turbulent cascade propagates towards small scales in 3-D where it decays by molecular viscosity whereas 2-D cascades go to larger scales => life-times goes to infinity for 2-D for low viscosity)

This law results from quadratic invariants in mom.-energy equations

In compressible fluids, first order term do not vanish and LT become similar (MHD-turbulence, e.g. Stein & Ostriker 2001) but still ...

- numerical viscosity is important (limited resolution)

Final Discussions and Conclusions

- Change of the physics of the thermonuclear runaway
  a) classical, spherical picture of compressional heat (Sato et al. 1976)
    -> rising blobs in a static WD (Garcia & Woosley 1995)
    -> (now) importance of initial velocity field

The explosion is determined by the precondioning of the WD !!!

- The chemical profile 'survives' the runaway but the central C/O increases from 23 % to 37%
    -> energy release during the deflagration phase is modified (scale of instabilities)
    -> reduction of jump in C/O by a factor of 3 and possible effect on the DD-transition
- Ignition occurs in one confined region (no multiple spots in our example. Is this true in general?
- Speed and structure of the deflagration front will be determined by the large scale velocity fields prior to the runaway